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The progress in the study of Arctic pack ice ecology

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Abstract The sea ice community plays an important role in the Arctic marine ecosystem. Because of the predicted environmental changes in the Arctic environment and specifically related to sea ice, the Arctic pack ice biota has received more attention in recent years using modern ice-breaking research vessels. Studies show that the Arctic pack ice contains a diverse biota and besides ice algae, the bacterial and protozoan biomasses can be high. Surprisingly high primary production values were observed in the pack ice of the central Arctic Ocean. Occasionally biomass maximum were discovered in the interior of the ice floes, a habitat that had been ignored in most Arctic studies. Many scientific questions, which deserve special attention, remained unsolved due to logistic limitations and the sea ice characteristics. Little is know about the pack ice community in the central Arctic Ocean. Almost no data exists from the pack ice zone for the winter season. Concerning the abundance of bacteria and protozoa, more studies are needed to understand the microbial network within the ice and its role in material and energy flows. The response of the sea ice biota to global change will impact the entire Arctic marine ecosystem and a long-term monitoring program is needed. The techniques, that are applied to study the sea ice biota and the sea ice ecology, should be improved.

Key words Arctic, sea ice, pack ice, ecology.

Sea ice is a main characteristic in both the Antarctic and Arctic seas, and most of them exist as pack ice. The pack ice in the Antarctic seas composes mainly of first-year ice, however, a large quantitive multi-year ice occurs in the Arctic Ocean. The covered area of permanent sea ice cover in the Arctic Ocean can be as large as 7.8×10^6 km^2, which constitute of more than half of the maximum of the covered area during winter.

The existence of the multi-year ice with several meter thickness restricts seriously the researches in this area. Although the research on the Arctic pack ice community can be traced back to the middle of 18 century, with the reasons of such as logistics, only scattered researches, mainly on the taxonomy of ice diatom, were carried out in the large area of pack ice, especially in the central Arctic Ocean in a long period. In recent years, because of the rapid change of ecological environmental conditions caused by the global change, and the increasingly decrease of ice covered area and ice stock, the research of pack ice ecology had been acquired much attention and made some progress. The opening of the Arctic area also provided the necessary condition for the research in the Arctic pack ice zone. In recent years, more new research data were obtained through different Arctic cruises and give us new knowledge for the Arctic pack ice community.

1 Primary production

At the beginning of the 90 th in 20 century, the primary production in the Arctic seas was commonly accepted as 2.14-2.78 × 10^{14} $g \cdot C \cdot a^{-1}$, among which about 25% came from sea ice community (Legendre *et al*. 1992). However, the recent studies suggested that the primary production from sea ice, especially from pack ice might be underestimated obviously.

Firstly, because of the absence of *in situ* measured data, the primary production in pack ice (600 $mg \cdot C \cdot m^{-2} \cdot a^{-1}$) in the above estimation was calculated from the difference of POC concentrations between summer and winter. However, the investigation results of the joint US-Canada cruise in 1994 showed, the primary production of pack ice along the transect in Arctic Ocean (Chukchi Sea-Arctic Point-Greenland Sea) ranged from 0.5 to 310 $mg \cdot C \cdot m^{-2} \cdot day^{-1}$, with an average of 33 $mg \cdot C \cdot m^{-2} \cdot day^{-1}$. In the center Arctic Ocean, the average value of the primary production within pack ice was as high as 57 $mg \cdot C \cdot m^{-2} \cdot day^{-1}$ (Gosselin *et al*. 1997). If the average value in the whole transect and the growth period of 180d per year (including spring and summer seasons, the condition in the former estimations was adopted) were used, the primary production in the Arctic pack ice might be underestimated about one magnitude lower. Thus the constitution of primary production in the Arctic sea ice to the total would be increased from 1/4 to 1/3.

Secondly, most of the former studies concentrated only on the bottom several centimeters of pack ice, based on the fact that the ice algal blooms occurred normally in the bottom of pack ice during spring and summer. However, the studies for the whole ice cores from the pack ice in the Greenland Sea showed, the peaks of ice algal biomass could exist in the interior of sea ice, and the primary production per square meter in the interior of sea ice may exceed those in the bottom (Gradinger 1999; Mock and Gradinger 1999). Furthermore, recent study suggested that ice algal bloom occurred in the bottom of sea ice in autumn, and the integrated biomass could even higher than those in spring and summer (Werner and Gradinger 2002). The actual growth period of ice algae should be longer than 180 d per year.

Even so, considering the patchy distribution of sea ice community and the obvious inter-annual variations (Hegseth 1998), a relative accurate estimation of primary production should base on more research data.

2 Spatial distribution of community and biomass

Ice algae were the most important assemblages in the pack ice, and the biomass peaks occurred mainly in the lower sections, especially in the bottom several centimeters. For this reason, early studies usually focused on the bottom community. Within Arctic pack ice, especially within the multi-year pack ice with several meter thickness, the interior community has been ignored in most Arctic studies and understood preliminarily only in recent years.

The characteristics of the ice algal assemblages depended on their spatial position within the ice. Snow algae were common in the upper and surface layers and the abundance could reach 1.56×10^5 cells ml^{-1} in the central Arctic Ocean (Gradinger and N•rnberg 1996). Autotrophic flagellates and spores dominated in the upper sections of sea ice, and the dominant species in the lower sections was pennate diatoms. Commonly, the biomass in the bottom of sea ice was highest and could be more than 1000 $\mu g \cdot C \cdot l^{-1}$ (Booth and Horner 1997; Gradinger 1999a). However, a color layer of 10 cm thickness was found in the interior section of 50 cm depth from the surface during the Greenland Sea cruise in autumn 1999. The biomass was near 500 $\mu g \cdot C \cdot l^{-1}$ (unpublished data). *Melosira arctica* dominated the ice-water interface assemblages. It commonly grew as algal strains and formed algal mat on the bottom of the multi-year pack ice. The algal strains could be extended as long as several meters. Based on the estimation of Melnikov, the distribution of *Melosira arctica* algal mats on the bottom of pack ice was about 2% of the total covered area (Melnikov 1997), and played an important role in the Arctic pack ice ecosystem and carbon biogeochemistry cycle. The research on a single floe in winter showed that the abundance, biomass and biodiversity were low (Druzhkov *et al*. 2001).

Similar with ice algae, peaks of the pack ice bacteria were observed either in the bottom or interior of sea ice, or several peaks occurred in the same ice core. The peaks of bacteria had no relationships with that of ice algae, however, their sizes related to the ice algal biomass. Bacteria played an important role in the interior community of pack ice, and the maximum ratio of integrated biomass of bacteria to ice algae could be as high as 10 : 1 (Gradinger and Zhang 1997). Gradinger reported that the average biomass of pack ice community in summer and autumn were 0.2 g·C·m^{-2}, of which ice algae constituted 43%, followed by bacteria (31%), heterotrophic flagellates (20%) and mesometazoa (4%) (Gradinger *et al*. 1999). It suggested the significance of the microbial loop in the pack ice community.

The size and distribution of metazoa within the ice were limited by the space of the brine channel, and concentrated mainly in the bottom several centimeters. The abundances of metazoa in the pack ice of the Canadian Arctic were dominated by copepods and nauplii, however, nematods dominated in the pack ice of the central Arctic Ocean (Nozais *et al*. 2001; Gradinger 1999b). Acoel turbellarians also had high abundance in the Arctic pack ice (Friedrich and Hendelberg 2001). In the Greenland Sea, the abundance of amphipods living in the ice-water interface reached its maximum of 31.9 ind. m^{-2} in summer (Werner and Gradinger 2002). The food was enough for the fauna living in the pack ice in the central Arctic Ocean, however, obvious grazing pressure for the ice algae might exist in the Greenland Sea (Gradinger *et al*. 1999; Gradinger 1999b).

3 Biodiversity

Pack ice contains a complicate community, including viruses, bacteria, autotrophic algae (diatoms and autotrophic flagellates), protozoa (heterotrophic flagellates and ciliates, ect.) and metazoa (rotifer, copepods, nauplii and amphipods, ect.).

Among all of the pack ice assemblages, only the history of studing diatoms is long, in which near 300 species has been reported. In recent years some new genus such as *Fussila* and *Craspedopleura* were reported. Although the high abundance and biomass of flagellates were reported in the interior of sea ice (Gradinger 1999a; Gradinger *et al*. 1999), and might play an important role in the pack ice community during the winter (Okolodkov 1992), the research of taxonomy of them were scarce for the neglect and relative difficulty of identification (Hegseth 1998). In recent years, the phylogenetic tree of the bacteria in the pack ice has been done with molecular genetic methods based on partial 16S rRNA and 16S rDNA sequence (Brown and Bowman 2001; Junge *et al*. 2002), showing the low diversity and some homology with the Antarctic assemblages. The species of metazoa were few and the identified species of rotifers and amphipods were only 8 and 4, respectively (Friedrich and De Smet 2000; Poltermann 2001). However, except the sea ice diatoms, the taxonomy researches for other assemblages were limited. It's too early to educe the conclusion of low biodiversity.

4 Environmental regulation

The researches in this aspect were limited and most of them depended on simulated experiments and model analysis. Because it took much time for each station to collect samples and environmental data, the stop ice stations were limited during each cruise and the *in situ* experiments and usually process researches were difficult to arrange. Furthermore, the mini-habitats within ice were complex and different source and age might occur in border upon ice floes, even in the same floe. All these increase the difficulties of environmental regulation researches.

Light might be the most important factor in control the structure and biomass of the pack ice community. The light regulation experiment *in situ* through the change of thickness of covered snow suggested that in the natural condition, the algal assemblage composed mainly of flagellates and diatoms, and rotifers dominated the heterotrophic assemblages. Decrease of light caused the gradual decrease of the biomass of the whole community. Contrastively, increase of light led to a large biomass, and the diatoms and ciliates became dominant, replacing the flagellates and rotifers (Gradinger *et al*. 1991).

The models showed that the physical structure, temperature and brine volume of sea ice all could influence the relationships between grazers and their foods, so would influence the process of sea ice food web dynamics (Krembs *et al*. 2002). It was reported that the topography of the bottom of sea ice influenced obviously the distribution of ice algae and amphipods in the bottom of sea ice. The abundance of the amphipod *Apherusa glacialis* related to hydrography of the ice-water interface and the ice algal biomass in the bottom of sea ice (Hop *et al*. 2000; Krembs *et al*. 2002; Werner and Gradinger 2002). Furthermore, the sea ice conditions such as the size of the floe played a more important role in the population structure than the age of sea ice (Beuchel and Lnne 2002).

5 Ecological role

The organisms in the upper water column, especially the large diatoms, could be incorporated into the sea ice during the formation of the sea ice (Gradinger and Ikävalko

1998). During melting seasons in spring and summer, the organisms within ice would be released into the seawater. With such a mechanism, the sea ice could redistributed micro-organisms through the circumfluence in the Arctic Ocean and Outflow Current in the Fram Strait. Beside the directly contribution to the primary production in the Arctic seas, ice algae could play "seeds" of ice-edge phytoplankton bloom during the melting period in spring, although this role had obviously inter-annual variations. Recent research showed that some bioactive soluble material(s) produced within the bottom-ice algal layer acted as a "conditioning" agent that enhanced the growth of phytoplankton in Arctic waters. The effect of such material(s) was similar with additions of ethylenediamine tetra-acetic acid (EDTA) or trace metals (Apollonio *et al*. 2002).

Pack ice community supported an ice-water interface community, in which a typical assemblage was amphipods. They were omnivorous, and their food sources included organic detritus, ice algae and *Calanus* species living in the ice-water interface (Poltermann 2001; Scott *et al*. 2001; Werner *et al*. 2002). The research also found, the *Calanus glacialis*, a dominant species in the Arctic waters, grazed ice algae on the bottom of the pack ice in summer (Werner and Martinez Arbizu 1999). The occurrence of the amphipods on the bottom of pack ice could accelerate the downward transportation of carbon in the sea ice. The production of fecal pellets was 0.7 $mg \cdot C \cdot m^{-2} \cdot day^{-1}$, which constitute of about 2% of the carbon in the bottom 2 cm (Werner 2000).

Ice algae were also an important source of DMS and bromoform ($CHBr_3$), destroyed the ozonosphere in the Arctic atmosphere, and would have a feedback to the global change (Sturges *et al*. 1992; Levasseur *et al*. 1994; Cota and Sturges 1997).

6 Question and prospect

Restricted by the logistics, the data for the pack ice community were limited and many scientific questions remained unsolved. Because of the complexity of the ice conditions and interior mini-habitats of the Arctic pack ice, especially for the multi-year pack ice, some chanciness existed as the data collection on a few ice stations and the representation of the ice stations were inferior to sea stations. Furthermore, the researches in the Arctic pack ice zone were imbalance. Most of the researches were concentrated in the Arctic seas near the side of the Atlantic Ocean. It's necessary to increase the Arctic cruises, enlarge the investigation areas and develop new research areas in order to understand exactly the characteristics of pack ice community and its ecological role in the Arctic marine ecosystem. The author thinks that the following aspects should be included in the further investigations and researches:

6.1 *The studies in the central Arctic Ocean or in winter*

The study on the multi-year ice and underlying waters in the central Arctic Ocean in summer suggested that the primary production in this area were at least 10 times than that estimated before, and ice algae constitute 57% of the total primary production (Gosselin *et al*. 1997). This study changes the traditional concept of low biological activity under the Arctic permanent sea ice cover. However, inter-annual variation might occur in the sea ice community, only one cruise was not enough. At present the study on the Arctic pack ice community in autumn has been enhanced. Contrastively, the knowledge about the pack ice community in winter was few because of the logistic difficulty during the winter (Druzhkov *et al*. 2001). It was reported that ice algae grew both in the ice-snow interface and interior of pack ice in the Antarctic pack ice zone during austral winter, and the chlorophyll a concentrations were higher than those in the underlying water column. The research also showed that the ice algae might be a main food source of the Antarctic krill in winter when the foods were scarce in underlying seawater (Stevens 1995; Melnikov 1998). How about the community in the Arctic pack ice in winter? It deserves attention.

6.2 *The study on the microbial loop*

The integrated biomass or primary production in the interior of sea ice could exceed those in the bottom several centimeters (Gradinger 1999a; Mock and Gradinger 1999). In order to have a relatively comprehensive understanding of the Arctic pack ice community, the traditional method of only focusing on the bottom of sea ice where the biomass were usually high should be changed in the further studies. Limited by the mini-habitat, the biomass of metazoa within the ice were low, especially in layers other than the bottom of the ice. So it can be expected that the microbial loop will play an important role in the pack ice ecosystem. Little information is available on the pico-algae, viruses and the carbon/energy flows within the microbial loop in the pack ice community.

6.3 *The response of Arctic pack ice community to global change*

Influenced by the global change, the ice covered area in the Arctic waters has being decreased with an average rate of 2.8% per decade since 1978. And the average thickness decreased 43% in middle 90 th of 20 century comparing with that in later 50th (Parkinson *et al*. 1999; Kerr 2002). The change described above would influence the primary production, community structure and the whole ecosystem in the Arctic waters (Krajick 2001). Due to the quick thaw of sea ice, ice algae will be replaced by the phytoplankton, or indeed replaced by the salt and fresh water algae. The food chain depended on the ice algae will be damaged. Furthermore, the survival of animals such as Arctic bears and seals which utilized ice floes as habitats will be threaten. It can be seen that the understanding of pack ice community and its ecological role is a key to know the extent of the effect on the Arctic marine ecosystem by pack ice variations. In reverse, the researches on the pack ice community and ecological changes can also reveal the influence of global change.

6.4 Improvement of the research techniques

Because sea ice is a complex mixture of ice and brine, most of recent researches were carried out after the ice had been melted in the filtered seawater to avoid osmotic stress. This method was widely used, however, shortcoming was obviously. This method can only decrease, but can't avoid the breakage of the fragility cells, especially the flagellates and protozoa, caused by the change of penetration pressure. Furthermore, the process of thawing will dilute the community originally occurred in the brine channels and pockets. It's difficult to keep the reliability of the experiment when such a technique was utilized. Although some *in situ* experiments were attempted (e.g. Mock and Gradinger 1999), but they are difficult to be widely applied.

Taking the Germany R.V. "Polarstern" icebreaker, as a main platform, the European carried out concentrated researches on the pack ice ecology in the Greenland and Barents Seas. However, for the reason of the history, the data in the Chukchi Sea and northern waters were scarce, and this area is the main investigation area of Chinese Arctic cruises. Relied on the R.V. "Xuelong", China had carried out two Arctic cruises in this area in summer of 1999 and 2003. Several ice stations had been set up in the Canadian Basin region. These works was helpful for our knowledge for the community of the Arctic pack ice, especially for the community in the central Arctic Ocean. It can be prospected that, China will contribute more to the researches on the ecology of the Arctic pack ice, regardless of her late participation in the Arctic cruises.

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References

Apollonio S, Pennington M, Cota GF (2002): Stimulation of phytoplankton photosynthesis by bottom-ice extracts in the Arctic. Polar Biol., 25: 350-354.

Beuchel F, L•nne OJ (2002): Population dynamics of the sympagic amphipods *Gammarus wilkitzkii* and *Apherusa glacialis* in sea ice north of Svalbard. Polar Biol., 25: 241-250.

Booth BC, Horner RA (1997): Microalgae on the Arctic Ocean section, 1994: species abundance and biomass. Deep-Sea Res. Ⅱ, 44: 1607-1622.

Brown MV, Bowman JP (2001): A molecular phylogenetic survey of sea-ice microbial communities (SIMCO). Microbiol. Ecol., 35: 267-275.

Cota GF, Sturges WT (1997): Biogenic bromine production in Arctic. Mar. Chem., 56: 181-192.

Druzhkov NV, Druzhkova EI, Kuznetsov LL (2001): The sea-ice algal community of seasonal pack ice in the southwestern Kara Sea in late winter. Polar Biol., 24: 70-72.

Friedrich C, De Smet WH (2000): The rotifer fauna of arctic sea ice from the Barents Sea, Laptev Sea and Greenland Sea. Hydrobiologia, 432: 73-89.

Friedrich C, Hendelberg J (2001): On the ecology of Acoela living in the Arctic Sea ice. Belgian J Zool., 131: 213-216.

Gosselin M, Levasseur M, Wheeler PA *et al*. (1997): New measurements of phytoplankton and ice algal production in the Arctic Ocean. Deep-Sea Res. Ⅱ, 44: 1623-1644.

Gradinger R (1999a): Vertical fine structure of the biomass and composition of algal communities in Arctic pack ice. Mar. Biol., 133: 745-754.

Gradinger R (1999b): Integrated abundance and biomass of sympagic meiofauna in Arctic and Antarctic pack ice. Polar Biol., 22: 169-177.

Gradinger R, Friedrich C, Spindler M (1999): Abundance, biomass and composition of the sea ice biota of the Greenland Sea pack ice. Deep-Sea Res. Ⅱ, 46: 1457-1472.

Gradinger R, Ik? valko J (1998): Organism incorporation into newly forming Arctic sea ice in the Greenland Sea. J. Plankton Res., 20: 871-886.

Gradinger R, N•rnberg D (1996): Snow algal communities on Arctic pack ice floes dominated by *Chlamy-*

domonas nivalis (Bauer) Wille. Proc. NIPR Symp. Polar Biol., 9: 35-43.

Gradinger R, Spindler M, Henschel D (1991): Development of Arctic sea-ice organisms under graded snow cover. Polar Res., 10: 295-307.

Gradinger R, Zhang Q (1997): Vertical distribution of bacteria in Arctic sea ice from the Barents and Laptev Seas. Polar Biol., 17: 448-454.

Hegseth EN (1998): Primary production of the northern Barents Sea. Polar Res., 17: 113-123.

Hop H, Poltermann M, Lonne OJ *et al*. (2000): Ice amphipod distribution relative to ice density and under-ice topography in the northern Barents Sea. Polar Biol., 23: 357-367.

IkLvalko J, Gradinger R (1997): Flagellates and heliozoans in the Greenland Sea ice studied alive using light microscopy. Polar Biol., 17: 473-481.

Junge K, Imhoff F, Staley T *et al*. (2002): Phylogentic diversity of numerically important Arctic sea-ice bacteria cultured at subzero temperatures. Microbiol. Ecol., 43: 315-328.

Kerr RA (2002): Whither Arctic ice? Less of it, for sure. Science, 297: 1491.

Krajick K (2001): Arctic life, on thin ice. Science, 291: 424-425.

Krembs C, Gradinger R, Spindler M (2000): Implications of brine channel geometry and surface area for the interaction of sympagic organisms in Arctic sea ice. J. Exper. Mar. Biol. Ecol., 243: 55-80.

Krembs C, Tuschling K, Juterzenka KV (2002): The topography of the ice-water interface-its influence on the colonization of sea ice by algae. Polar Biol., 25: 106-117.

Legendre L, Ackley SF, Dieckmann GS *et al*. (1992): Ecology of sea ice biota 2. Global significance. Polar Biol., 12: 429-444.

Levasseur M, Gosselin M, Michaud S (1994): New source of dimethylsulfide (DMS) for the arctic atmosphere: ice diatoms. Mar. Biol., 121: 381-387.

Melnikov IA (1997): The Arctic sea ice ecosystem. Goedon and Breach Science Publishers.

Melnikov IA (1998): Winter production of sea ice algae in the western Weddell Sea. J. Marine Syst., 17: 195-205.

Mock T, Gradinger R (1999): Determination of Arctic algal production with a new and easy *in situ* incubation technique. Mar. Ecol. Progr. Ser., 177: 15-26.

Nozais C, Gosselin M, Michel C *et al*. (2001): Abundance, biomass, composition and grazing impact of the sea-ice meiofauna in the North Water, northern Baffin Bay. Mar. Ecol. Progr. Ser., 217: 235-250.

Okolodkov YB (1992): Cryopelagic flora of the Chukchi, East Siberian and Laptev Seas. Proc. NIPR Symp. Polar Biol., 1992, 5: 28-43.

Parkinson CL, Cavalieri DJ, Gloersen P *et al*. (1999): Arctic sea ice extents, areas, and trends, 1978-1996.

J Geophys. Res.-Oceans, 104 (C9): 20837–20856.

Poltermann M(2001): Arctic sea ice as feeding ground for amphipods - food sources and strategies. Polar Biol., , 24: 89–96.

Scott CL, Falk-Petersen S, Gulliksen B *et al*. (2001): Lipid indicators of the diet of the sympagic amphipod *Gammarus wilkitzkii* in the Marginal Ice Zone and in open waters of Svalbard (Arctic). Polar Biol., 24: 572–576.

Scott CL. Falk-Petersen S, Sargent JR *et al*. (1999): Lipids and trophic interactions of ice fauna and pelagic zooplankton in the marginal ice zone of the Barents Sea. Polar Biol., 1999, 21: 65–70.

Stevens JE (1995): Antarctic pack-ice ecosystem. BioScience, 45: 128–132.

Sturges WT, Cota GF, Buckley PT (1992): Bromoform emission from Arctic ice algae. Nature, 358: 660–662.

Werner I (2000): Faecal pellet production by Arctic under-ice amphipods-transfer of organic matter through the ice/water interface. Hydrobiology, 426: 89–96.

Werner I, Auel H, Friedrich C (2002): Carnivorous feeding and respiration of the Arctic under-ice amphipod *Gammarus wilkitzkii*. Polar Biol., 25: 523–530.

Werner I, Gradinger R (2002): Under-ice amphipods in the Greenland Sea and Fram Strait (Arctic): environmental controls and seasonal patterns below the pack ice. Mar. Biol., 140: 317–326.

Werner I, Martinez AP (1999): The sub-ice fauna of the Laptev Sea and the adjacent Arctic Ocean in summer 1995. Polar Biol., 21: 71–79.